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ON THE RELATIONSHIP OF X-RAY EMISSION OF SOLAR FLARES WITH THEIR EFFECTS IN COSMIC RAYS

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SUMMARY

From the comparison of ionospheric effects of flares with small increase in cosmic ray intensity (less than one percent) at sea level (nucleon component), it follows that:

1) to more powerful effects in the D-layer of the ionosphere correspond, as an average, more substantial increases of cosmic ray intensity at sea level;

2) the appearance of absorption in the D-layer, that is of an X-ray flux with $\lambda \leqslant 8$ Å constitutes a necessary but not sufficient indication of the occurrence of a small effect in cosmic rays at sea level.

* * *

1. The detection by direct measurements of the electron component of solar cosmic rays [1] arouses interest in the question of its possible investigation by indirect methods on the basis of the already available material.

As is well known, the accelerated electrons are manifest in the solar atmosphere by a synchrotron emission in the radioband and in the visible region of the spectrum (see for example, [2, 3]), and also in the bremsstrahlung emission in the X-ray region of the spectrum.

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* O SVYAZI RENTGENOVSKOGO IZLUCHENIYA SOLNECHNYKH VSPYCHEK S IKH EFFEKTAMI V KOSMICHESKIKH LUCHAKH.

Various viewpoints are currently expressed about the nature of X-ray radiation of flares. For example, in ref. [4] it is assumed that the X-ray emission is entirely unbalanced. — On the other hand, attempts are now made to explain the available basic data by equilibrium emission of plasma at temperatures of the order of 10^7 °K, and higher [5, 6].

The object of this work is to study the question of relationship between the effects of solar flares in cosmic rays on the one hand, and the X-ray emission of flares on the other. This may contribute to obtaining additional data on the nature of X-ray emission of flares and to ascertaining the possibility of studying the electron component of solar cosmic rays by its X- ray emission.

According to the opinion of many authors [7 – 14], a sudden increase in electron concentration in the D-layer of the ionosphere during solar flares is induced by a sudden increase of X-ray flux with $\lambda \leqslant 8$ Å. This leads to a sudden increase of the absorption of cosmic radio emission (SCNA) and of short radiowaves (SWF), and also to a series of other events.

When comparing in the present work the X-ray emission of solar flares with the increase in intensity of cosmic rays, we shall use as a basis the indirect (ionospheric) methods of detection of X-ray radiation and not on the direct measurements. That is why, when in the following there will be question of "X-ray flux with $\lambda \leqslant 8$ Å", it should be understood that reference is made to the corresponding effects in the D-layer, induced by the said flux. Note also, that the ionosphere effects, referred to, correspond to middle and low latitudes, i. e. they are caused by a wave rather than corpuscular radiation of solar flares.

2. - We used as the indicator of X-ray emission of flares in the region $\lambda \leqslant 8$ Å the data on minimum reflection frequencies from the ionosphere at vertical sounding — f_{min} (according to "MTSD"B-2 material), on absorption of short radiowaves – SWF [15], on the absorption of cosmic radio emission – SCNA [15, 16] and on sudden increase of atmospherics — SEA [15].

The effects of solar flares on f_{min} were sorted by the method expounded in [17], by material from ionospheric stations, also indicated in that reference. The intensity of the effects on f_{min} was estimated by a three-number scale.

The data on the intensity of the nucleon component of cosmic rays at sea level were borrowed from [18] and from the "MTSD" B-2 material.*

For flares, attended by great increase in intensity of cosmic rays at sea level, the amplitudes of the increases were borrowed from the literary data by stations with latitude of $\sim 50^{\circ}$, taking into account the zones of entry.

The time-integrated fluxes of solar cosmic rays, having induced absorptions in the polar cap, were borrowed from [19].

Also utilized were the data on radio emission of solar flares with $\lambda = 10$ cm [20].

3. - As is well known, the relativistic part of the energy spectrum of cosmic rays is less subject to variations of the conditions of propagation in interplanetary space than the nonrelativistic one; this is due to the substantially greater length of the free part. That is why, when studying the relationship of the X-ray emission of flares with the effects on cosmic rays, we utilized the relativistic part of the energy spectrum of solar cosmic rays.

The effects of flares on cosmic rays were studied separately for flares of force 2^{+} and more in H_{α}, of force 2 and of force less than 2.

Flares of force 2^{+} and above in H_{α}.- We selected for the analysis 27 flares in H_{α}, mainly of force 2^{+} and higher, for the IGY period. These flares were broken down into two groups, according to the presence of SWF (these data being the most complete): a) flares attended by SWF - 22 cases (Table 1); b) flares, when no SWF were observed — 5 cases (Tab.2). The unambiguity of the breakdown was corroborated by the data on f_{min} and on SEA.

The intensity of cosmic rays in a certain time interval, including the flare, was first averaged by eight high-latitude stations (Table 3). The corrections for the daily effect were not introduced, for the latter is relatively small for these stations. The time interval included near 8 hours preceding the flare, so that the quiet level of cosmic rays could be determined, and near 8 hours after it, so that the total period of increased cosmic ray intensity could be encompassed as far as possible.

*[in transliteration]

After that, the method of epoch superimposition was applied separately for each group.

TABLE 1

DATE	COMM.	FORCE in H
29.VIII 1957	05^h45^mE	2
29.VIII	10 31	2
10.IX	02 23	3
21.IX	13 30	3
30.IX	16 57	3
16.X	01 52	3
17.XII	07 34E	2
28.XII	22 29	2
25.I 1958	09 15E	3
1.III	09 05	3
7.IV	10 10	3
1.V	21 15	3
5.V	03 56	3
19.VI	09 40	3
19.VII	19 05	2+
4.VIII	04 09	3
14.IX	08 22	2+
19.X	06 58	2+
21.X	23 18	2+
24.X	14 32	2+
14.XI	00 36	3
24.XI	16 07	3

TABLE 2

22.VII 1957	09^h53^mE	3
29.VIII	13 33E	2
2.IX	10 45	2+
29.XI	00 45	3+
5.III 1958	05 00E	3

TABLE 3

STATION	Hardness cut-off thrshold Bev/s	Stat. error for 2 hours %
Churchill	0.3	0.53
Deep River	1.3	0.31
Leeds	1.6	0.56
Mawson	0.2	0.38
Murch.Bay	0.1	0.45
Resolute Bay ..	0	0.50
Sal'fur M......	1.1	0.23
Thule	0	0.50
Upsala	1.3	0.44

The results are plotted in Fig. 1 (A and B). The two-hour time interval are in abscissa. The time of flare commencement in H_α is taken for the zero time. Plotted in ordinates is the intensity of cosmic rays. Dashes indicate the mean values of cosmic ray intensity for the time interval before the flare. Vertical strokes denote the statistical errors of measurements, corresponding to averaging (this refers to both, Fig. 2 and 3). The last point's drop-out in Fig. 1 B is related to Forbush-drop for one of the events.

Flare of Force 2 in H_α. - 32 flares for basic force 2 were sorted in all, they answered the following requirements :

a) they were situated no farther than 60° to the west or to the east from the central meridian of the Sun;

b) the cosmic ray background was quiet at time of flare;

c) the level of geomagnetic field disturbance in the K_p- index was no higher than three in the time interval from 6 to 10 hrs after flare.

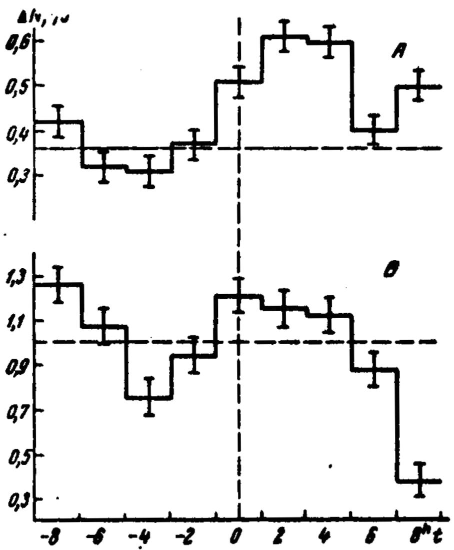

Fig. 1.- Effect in cosmic rays from flares in Hα of force 2+ (epoch suprimp.)

A — flares attended by SWF
B — flares not attended by absorption in the D-layer

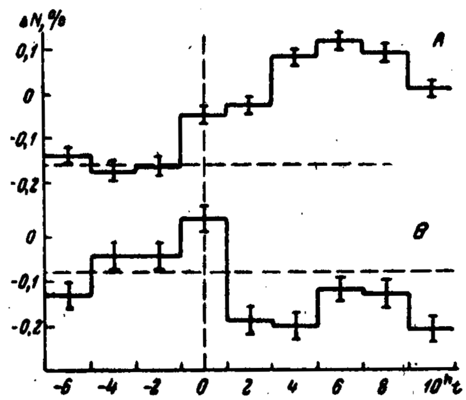

Fig. 2. - Effect in cosmic rays from flares in Hα of force 2 (epoch superp.)

A — flares attended by SWF;
B — flares not attended by absorption in the D-layer of the ionosphere.

For the flares thus selected the conditions of propagataion through interplanetary space were most favorable.

These flares were also broken down into two groups: with SWF — 20 cases (Tables 4 and 8), and without SWF — 12 cases (Table 5). As in the preceding case, the unambiguity of the breakdown was corroborated by data on f_{min} and SEA.

For these flares, the averaging of cosmic ray intensity was made by 25 stations (Table 6), and the daily effect was excluded by the preceding or following day. After that, the epoch superimposition method was applied.

The results are plotted in Fig. 2 (A and B). From the consideration of the graphs in Figs. 1 and 2 it follows, that the flares, attended by SWF, i. e. by a flux of X-ray radiation with $\lambda \leqslant 8$ Å, result in notable effects in cosmic rays ($\sim 0.3 \pm 0.03\%$). At the same time, flares not accompanied by notable increase in the ionization of the D-layer, i. e. without SFW, even if they provide effects in cosmic rays the latter are of the statistical error order. An identical conclusion was arrived at in [21].

It should be stressed, that for flare groups of force 2 and 3 in H_α, essentially different criteria for sorting and — processing methods were applied (see above).

TABLE 4

DATE	COMM.	FORCE IN H
1.IV 1958	10h50mE	2+
3.VIII	21 42	2
12.VIII	04 19	2
15.X	10 23	2+
18.X	01 34E	2
'11.XII	03 55	2

TABLE 5

24.XI 1957	19h30m	2
19.V 1958	10 52	2
3.VI	03 34	2
5.VI	02 58	2
5.VI	22 57	2
20.VI	00 16	2
15.VII	22 36E	2+
23.VII	05 18	2
14.VIII	04 37E	2
3.X	23 12	2
7.X	19 50	2
15.XII	06 24	2

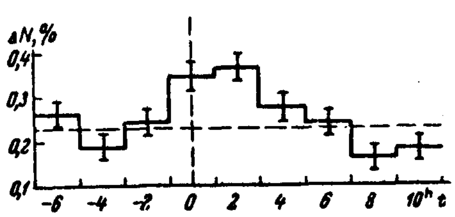

Fig. 3.- Effect in Cosmic Rays from flares in H_α of force < 2, attended by SCNA

TABLE 6

STATION	Stat.Error for 2 hrs %
Alma-Ata	0.38
Berkley	0.45
Chicago	0.48
Churchill	0.53
Climax	0.12
Deep River	0.31
Gottingen	0.41
Germanus	0.44
....	0.31
Leeds	0.56
Lincoln	0.52
London	0.41
Mawson	0.38
Mt.Wellington	0.37
Mt.Washington	0.28
Murchison Bay	0.45
Ottawa	0.52
Rome	0.56
Sal'fur M	0.23
Resolute Bay	0.50
Thule	0.50
Upsala	0.44
Weisenau	0.43
Zugspitze	0.15
Yakutsk	0.55
M. Norikura	0.20

Flares of Force < 2 in H_α .- As is well known [22], the effects in cosmic rays from flares of force 1 in H_α were not detected from the materials of IGY and IYQS. It is interesting to note, however, that the group of 9 flares of force < 2 in H_α (Table 7), especially studied by us and which were attended by an increase in the absorption of cosmic radio emission — SCNA, reveals a small rise of ΔN ($0.13 \pm 0.03\%$) (Fig. 3). The criterion of sorting and the method of processing for that group of flares was similar to that utilized for flares of force 2.

TABLE 7

DATE	COMM.	FORCE in H_α	DATE	COMM	FORCE IN H_α
4.V 1958	16^h33^m	1	12.IX	16^h05^m	1+
5.V	20 25	1+	16.X	17 05	1
13.VI	17 13	1+	20.X	19 12	1+
26.VII	19 52	1+	1.XI	18 15	1
14.VIII	21 37	1+			

On the basis of direct observations of X-ray radiation during solar flares it was established in [23], that the flux of X-ray radiation in the region $\lambda \leq 8\,\text{Å}$ with energy greater than $2 \cdot 10^{-3}$ erg/cm^2.sec is attended by SWF and other ionosphere effects. That is why, drawing the balance sheet of the above considerations, we may conclude that flares with such energy in the region $\lambda \leq 8\,\text{Å}$ provide, as an average, an increase in cosmic ray intensity at sea level of the order of 0.3 %, whereas flares with X-ray flux energy less than $2 \cdot 10^{-3}$ erg/cm^2 sec, even if they result in rise of ΔN, it will be less than 0.03%, the latter not depending at the same time on the flare in H_α.

It should be noted that none of the above-referred to groups of flares in H_α, included any of the well known flares, having given great intensity increases of cosmic rays at sea level.

4. — It would be interesting to see further whether there is a quantitative relationship between the magnitude of the ionospheric effect of a solar flare and the amplitude of the increase in cosmic rays. At sea level the latter was known for 10 flares [24].

The increases in intensity of the nucleon component of cosmic rays at sea level (ΔN) are compiled in Table 8. The flares accompanied by large ionospheric effects are marked by stars.

TABLE 8

DATE	COMM.	Force SWF	Force f_{min}	N %	DATE	COMM	Force SWF	Force f_{min}	N %
*28 Aug.57	08 41 E	3	3-	0.6	7 Jul.58*	00 20	3	3	0.5
11 Sep.	02 36 E	3	1+	0.1	29 Jul.*	02 59	3+	3	0.9
26 Sep.	19 07	2+	2-	0.3	16 Aug.*	04 33	3+	3+	0.2 ?
20 Oct *	16 37	3+	3	0.5	19 Aug.	00 42	2	1 }	
9 Feb.58	21 08	1	1	0.3	20 Aug.	21 18	2+	2- }	0.1
4 Apr.	21 47	2+	1+	0.1					

The values of ΔN, computed separately for flares having resulted in the most powerful ionospheric effects 'force 3 by SWF and f_{min}), and for the remaining flares, are respectively equal to 0.54% and 0.2%. As may be seen, some link is hinted here. However, the estimate of the ionospheric effect by scale for more precise quantitative comparisons appears to be too rough. That is why the data on SCNA for 1958 - 1961 were resorted to. Unfortunately, the watching of these events encompasses only the time interval from 15 00 to 03 00 hours UT.

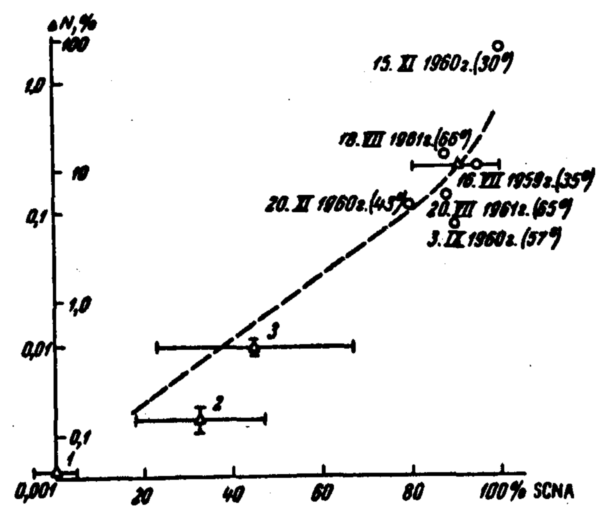

Fig. 4.- Relationship between the value of the absorption in the ionosphere and the cosmic rays' increase (ΔN, %).
The curve shows the conversion of absorption into monochromatic X-ray flux with $\lambda = 2$ Å (see text).

The results of such comparisons are plotted together in Fig. 4, where the values of absorption in percent (SCNA) are in abscissa, while the amplitude of cosmic ray intensity increase is represented in ordinates in logarithmic scale. The point 1 corresponds to the absence of absorption (SCNA = 0%) and to minimum increase of cosmic ray intensity, which may yet be revealed with the aid of the method of processing, applied for a given apparatus' sensitivity ($\Delta N = 0.05\%$).

Point 2 corresponds to the group of nine flares of force two in H_α, whose effect in cosmic rays is shown in Fig. 3 (Table 7). The value of the mean absorption for that group is 32% (standard deflection being ±15%). Point 3 corresponds to the mean effect of intensity increase for 14 flares, mainly of force 2 in H_α (Table 9). The magnitude of the mean absorption for this group of flares in 45 ± 22 %). The question arises, to what extent the SCNA with average values of 32 and 45% are typical respectively for flares of force 1 and 2 in H_α.

Plotted in Fig. 5 is the distribution of the number of cases of SCNA as a function of the value of absorption for the period 1958 - 1961, separately for flares of force 1, 2 and 3 in H_α. Besides, dashes indicate in Fig. 5 the absorption ranges 32 ± 15% and 45 ± 22% over the distributions for flares of force 1 and 2 in H_α, respectively. It may be seen from Fig. 5 that the amplitudes of SCNA for the points 2 and 3 in Fig. 4 are sufficiently characteristic for the corresponding forces of the flares in H_α.

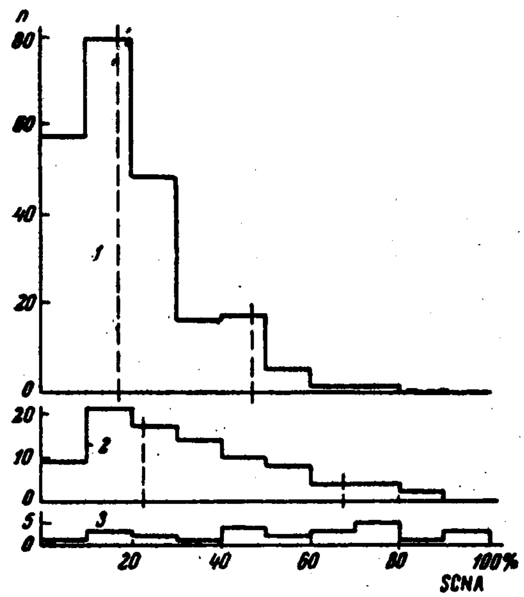

FIG. 5

Further, plotted in Fig. 4 are also six cases of great increases in the intensity of cosmic rays at sea level (data on SCNA were unavailable for the cases corresponding to 4 May and 12 November 1960).

Such somewhat artificial averaging procedure corresponds in fact to the method of obtaining the points 2 and 3 in Fig. 4, as in this case we do not know which flares were attended by cosmic ray increase at sea level, and which ones were not.

On the basis of all that, from Fig. 4 follows the conclusion, that there is, as an average, a dependence between the magnitude of SCNA and ΔN; this, however, is true only in average, for there are cases when significant absorption increases in the D-layer are not accompanied by intensity increase of cosmic rays at sea level. Thus, the appearance of absorption in the D-layer during a solar flare constitutes a necessary but insufficient sign for the appearance of cosmic ray intensity increase at sea level. This suggests the situation that arises when comparing type-IV radiobursts with the increases in intensity of cosmic rays.

For the sake of illustration, a curve, which is the result of conversion of the value of SCNA into the X-ray flux S beyond the atmosphere, expressed in ergs/cm^2 sec, is also plotted in the same Fig. 4. The X-ray flux was assumed monochromatic ($\lambda = 2$ Å), the height of the Sun above the horizon being 35°. The calculation was conducted by the method described in [25], with ionosphere parameters borrowed from [26, 27]. The scales for S and ΔN in Fig. 4 are so combined, that the flux of X-radiation $\sim 10^{-3}$ erg/cm^2·sec, constituting the threshold value for the detection of absorption in the D-layer, correspond to the value $\Delta N = 0.05\%$, beginning with which the increase in cosmic rays may be revealed with the help of the method applied above. It may be seen from Fig. 4 that the experimental points fit this curve satisfactorily.

As is well known, a good correlation is established between the intensity of radiobursts with $\lambda = 10$ cm and the X-ray emission of the flares [28, 29]. We took advantage of this for an independent verification of the mean dependence of ΔN on SCNA, established by us. The rises of cosmic ray intensity and the values of the smoothed radio emission fluxes for the Fig. 4 points are plotted in Fig. 6 using the double logarithmic scale.

Subsequently, it may also be seen from Fig. 7 that the dependence established for the relativistic part of the spectrum, is apparently noted for soft cosmic rays also. Unfortunately, data in regard to SCNA are known only for four cases, though all the events, with the exception of an extremely rare case, attended by polar blackout, are linked with flares.

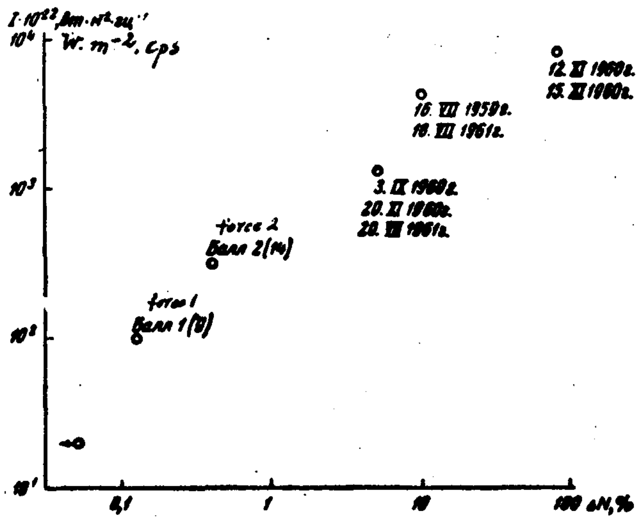

Fig. 6.- Dependence of the effect of cosmic ray intensity increase on the smoothed value of a radioburst at $\lambda = 10\,cm$) (the points' numbering corresponds to that of Fig. 4.).

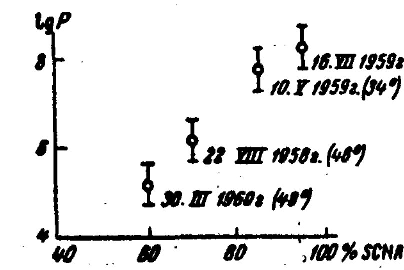

Fig. 7. - Dependence between the values of absorption in the ionosphere (SCNA) and the logarithm integrated over the time of cosmic ray flux with energy > 100 Mev (log P) [19] for four flares (the date is indicated near the point, alongside with the height of the Sun above the horizon for the station observing SCNA.

Drawing the balance sheet of all the above-expounded, we may reach the following conclusions :

1) There exists, as an average, a dependence between the value of absorption in the D-layer during a solar flare and the value of cosmic ray intensity increase at sea level.

2) The effect in cosmic rays is attended by a corresponding ionospheric effect in the D-layer, induced by the X-ray emission from solar flares in the region $\lambda \leq 8$ Å. However, the increase in cosmic ray intensity is not always observed in the presence of X-ray flux and of corresponding absorption in the D-layer.

The investigation of the nature of the regularities thus revealed will be the object of a separate communication.

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**** THE END ****

R E F E R E N C E S

1. P. MEYER, R. VOGT. Phys. Rev. Lett., 8, 387, 1962.
2. A. B. SEVERNYY. Izv. Krymskoy astrofiz. obs., 22, 67, 1960.
3. W. A. STEIN, W. P. NEY. J. Geophys. Res., 68, 65, 1963.
4. C. DE JAGER. Proc. of the 1-st Internat. Space Sci. Symposium, Nice, 1960.
5. K. A. KAWABATA. Tokyo Astron. Obs. Reprint, N 20, 1960.
6. H. FRIEDMAN. Proc. of IAU Symposium N 16, The Solar Corona, Cloudcroft, 1961.
7. N. A. SAVICH. O povedenii ionosfery vo vremya vnezapnykh vozmushchenyy (On the behavior of the ionosphere during the solar disturbances), Kahd. dissertatsiya, 1960.
8. N. N. ERYUSHEV. Izv. Krymskoy astrofiz. obs., 20, 3, 1958.
9. N. N. ERYUSHEV. Izv. Krymskoy astrofiz. obs., 26, 144, 1961.
10. N. N. ERYUSHEV, YU. I. NESHPOR. Izv. Krymskoy astrofiz. obs., 20, 12, 1958.
11. YU. I. NESHPOR. Izv. Krymskoy astrofiz. obs., 26, 156, 1961.
12. YU. I. NESHPOR, N. A. SAVICH. Izv. Krymskoy astrofiz. obs. 24, 41, 1960.
13. YU. I. VINOGRADOV, N. A. SAVICH. Izv. Krymskoy astrofiz. obs., 24, 48, 1960.
14. R. C. WITTEN, I. G. POPPOFF. J. Geophys. Res., 66, 2779, 1961.
15. Compilation of Solar geophys. data CRPL-F, part B, N 156 - 210, 1957 - 1961.
16. Rensselaer Obs. Publ., N 1 - 18, 1958 - 1960.
17. A. K. PANKRATOV. Izv. Krymskoy astrofiz. obs., 29, 160, 1963.
18. Cosmic Ray Intensity during IGY, Tokyo, 1959 - 1960.
19. E. L. CHUPP, R. W. WILIAMS. J. Phys. Soc. Japan, 17, Suppl. A-II, 281, 1962.
20. Quarterly Bull. Solar Activity of the I. A. U., N 119 - 136, 1957 - 1961.
21. B. I. WILSON, C. P. NEHRA. J. Geophys. Res., 67, 3707, 1962.

22. L. I. DORMAN, E. V. KOLOMEYETS. Geomagnetizm i aeronomiya, 1, 653, 1961.

23. R. W. KREPLIN, T. A. CHUBB, H. FRIEDMAN. J. Geophys. Res., 67, 2231, 1962.

24. B. M. VALDIMIRSKIY. Izv. Krymskoy astrofiz. obs., 28, 320, 1962.

25. YU. I. NESHPOR. Ionosfernyye issledovaniya, No. 10, 27, 1962.

26. M. NICOLET. A. C. AIKIN. J. Geophys. Res., 65, N 5, 1960.

27. A. P. MITRA. J. Geophys. Res., 64, 733, 1959.

28. O. HACHENBERG, A. KRUGER. J. Atm. Ter. Physics, 17, 20, 1959.

29. M. R. KUNDU. J. Geophys. Res., 66, 4308, 1961.

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